ENERGY ABSORPTION OF KEVLAR® FABRICS UNDER BALLISTIC IMPACT

JUN 1980

FRANK FIGUCIA
U. S. ARMY NATICK RESEARCH & DEVELOPMENT COMMAND
NATICK, MASSACHUSETTS 01760

Protection of the soldier from enemy threats is a multi-faceted research problem which requires study in many specialized areas of life support necessary for survival under combat conditions.

This paper considers one of these specialized areas, the prevention of debilitating wounds from fragmenting munitions. Specifically, it deals with protection by the use of flexible personnel armor made from fibrous materials.

Traditionally, the ballistic resistance of textile materials has been defined by laboratory measurement of ballistic limit (V_{50}), the velocity at which a material stops a simulated threat. This method has been widely accepted and it continues to serve the needs of the ballistic community; it is, however, very expensive and time consuming.

A new methodology has been developed at the U.S. Army Natick Research & Development Command (NARADCOM) which greatly reduces the cost and time necessary to develop equally reliable data. It generates a Ballistic Performance Indicator (B.P.I.) which can be used to predict the V_{50} ballistic limit, or to measure the relative ballistic usefulness of candidate materials.

This paper describes the new test methodology, compares experimental B.P.I. with actual V_{50} for five Kevlar materials, and suggests, through the use of B.P.I., fabric constructions for improved protection against fragmentation threats.

Kevlar® is the commercial designation for a polyaramid fiber manufactured by E. I. duPont deNemours & Co., Inc.

DEVELOPMENT OF TEST METHODOLOGY

The B.P.I. developed herein is based on an analysis of previously compiled data [1] for Kevlar materials subjected to ballistic impact. This data summarized V_{50} ballistic limit velocities over a wide range of areal densities, as shown in Figure 1.

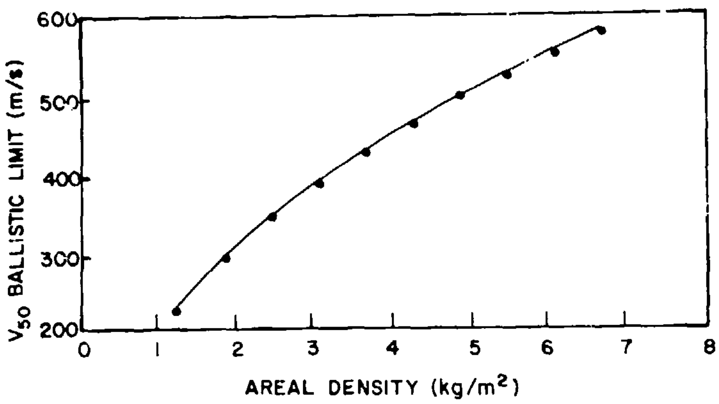

Figure 1. V_{50} Ballistic Limit vs. Areal Density For Kevlar Fabrics.

Conversion of the ordinate values of velocity to kinetic energy, by K.E. = $mV^2/2$, indicated that the energy absorbed at ballistic limit velocity is linear over the range of target densities examined, as seen in Figure 2.

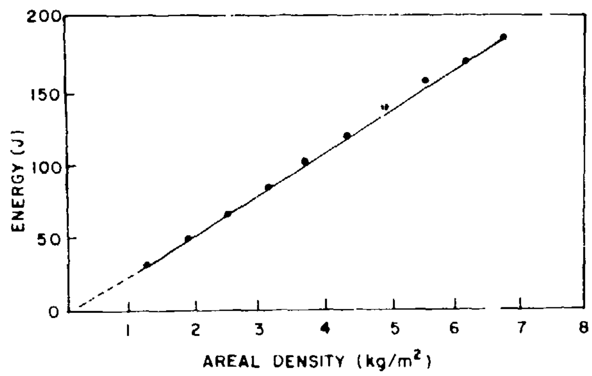

Figure 2. Energy Absorption vs. Areal Density For Kevlar Fabrics.

58

A

It was recognized that this trend could be effectively utilized, provided that this relationship was valid in the low energy, low areal density region, as extrapolated in Figure 2. Research scale equipment could then be used to generate energy absorption data with which to characterize behavior at higher levels.

An existing test facility, used for ballistic testing of yarns, was adapted for this purpose. The facility uses compressed helium gas to propel the standard 1.1 gram (17 grain) fragment simulating projectile. Electronic lumiline screens are placed before and after the target to provide time flight data for missile velocity calculations. These velocity data are then used, with appropriate corrections for aerodynamic drag between the screens and the target to calculate the energy absorbed by the target.

The target specimens are held between heavy aluminum plates in a specially designed fabric clamping device [2], shown in Figure 3. The device may be moved vertically and rotated, so that the five circular target openings cut from the plates are sequentially introduced into the path of the missile. Boundary conditions for all five impact points are equalized by this design. Therefore, anomolous variations in energy absorption, noted for other clamp designs investigated, are eliminated.

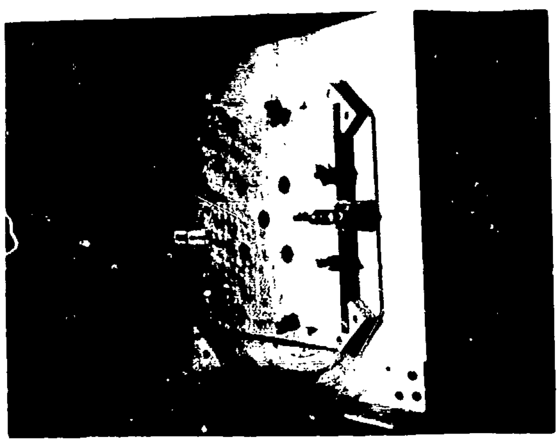

Figure 3. Rotatable Clamp For Testing Ballistic Fabric.

The following criteria were established to standardize test procedures.

(1) A complete screening consists of test firings at three striking velocities: 213, 274, and 366 m/s.

(2) At each velocity, tests are conducted starting with one layer of target material. Areal density is then varied by increasing the number of layers. The test sequence is continued until the target resistance approaches 50-60% of the available missile energy. Above this level, variability of individual readings increases significantly.

(3) Five replicate firings are used to generate one data point for a given test condition, i.e., number of layers/striking velocity.

RESULTS AND DISCUSSION

The new test procedure was first applied to a 170 g/m^2 Kevlar fabric made in a satin weave construction from 44 tex yarn. Tests were performed at the three velocities prescribed. The energy absorption for the various numbers of layers examined at each striking velocity are shown in Table 1.

Table 1. Laboratory Data For 170 g/m^2 Satin Weave Kevlar Fabric.

Striking Velocity (m/s)	Number of Layers	Areal Density (kg/m^2)	Energy Absorbed (J)
213	1	0.17	5.56
213	2	0.34	12.57
274	1	0.17	4.87
274	2	0.34	11.00
274	3	0.51	18.67
274	4	0.68	27.04
366	1	0.17	6.90
366	2	0.34	12.14
366	3	0.51	18.54
366	4	0.68	24.12
366	5	0.85	28.42
366	6	1.02	35.20

Reproducibility of individual values was excellent at low and medium energy absorption levels (coefficient of variation approximately equal to 3%). However, at target energy absorptions of 50% or more of total available missile energy, variability was observed to increase. The test sequence was therefore terminated when this level was approached.

The data from Table 1 were analyzed graphically and statistically to test for linearity. It is seen in Figure 4 that energy absorption and areal density are directly proportional over this low areal density range. It appeared, therefore, that the assumption of linearity in the extrapolated portion of Figure 2 was valid, and further investigation was warranted.

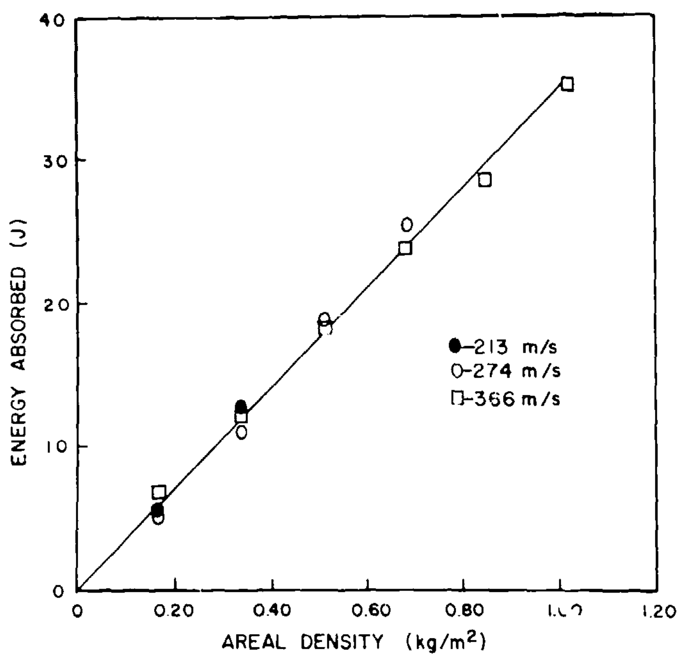

Figure 4. Energy Absorption of 170 g/m^2 Satin Weave Kevlar Fabric by Laboratory Screening Method.

A least squares fit regression of the data yielded a slope of 35.1, with a correlation coefficient of 0.99. It is this numerical value of the slope which is defined as the Ballistic Performance Indicator. It represents the energy absorbed per unit increase in areal density.

Similar data were generated for four additional Kevlar materials. Linearity was obtained in all cases, with a high degree of statistical confidence. The resultant B.P.I.'s obtained are recorded in Table 2.

61

Table 2. Ballistic Performance Indicators Obtained by Laboratory Analysis for Five Kevlar Fabrics.

Identification Number	Fabric Weight (g/m^2)	Fabric Weave	Fabric Yarn Tex	B.P.I. ($J/kg/m^2$)
1	170	Satin	44	35.1
2	294	Plain	111	29.7
3	278	Satin	111	32.9
4	464	Basket	111	24.9
5	464	Basket	167	22.6

Use of the B.P.I. to predict performance at higher levels is illustrated in Figure 5 for fabrics 1 and 4. The laboratory data are extrapolated to areal density levels at which conventional V_{50} tests were performed on the same materials. The projected energy absorptions compare closely to those calculated from actual V_{50} values.

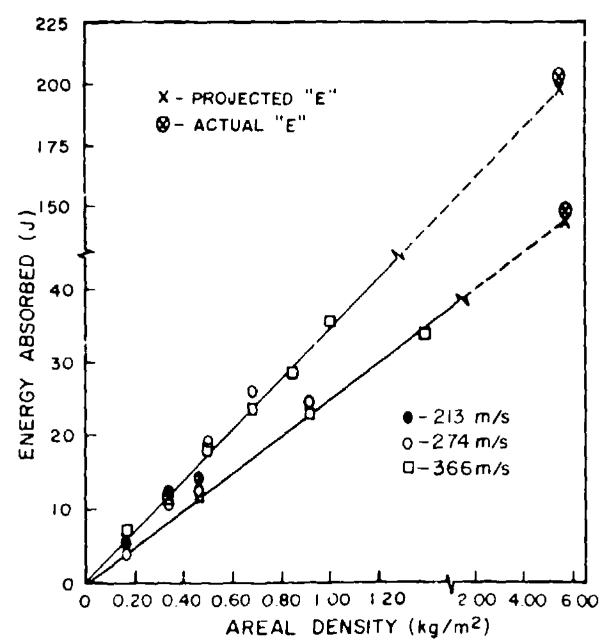

Figure 5. Projected and Actual Energy Absorption at Full Areal Density.

62

Table 3 summarizes projected and actual results for all five materials in terms of V_{50} ballistic limit velocities. A high degree of accuracy is indicated, with no actual value varying from the predicted by more than 2.1%.

Table 3. V_{50} Ballistic Limits of Five Kevlar Fabrics Obtained by Laboratory Prediction and Actual Test.

Identification Number	B.P.I. ($J/kg/m^2$)	A.D. (kg/m^2)	V_{50} Ballistic Limit (m/s) Predicted	Actual	% Difference
1	35.1	5.68	602	610	1.4
2	29.7	5.83	561	551	-1.8
3	32.9	5.72	585	573	-2.1
4	24.9	5.75	510	518	1.7
5	22.6	6.97	535	543	1.5

Use of the B.P.I. methodology to predict V_{50} provides significant advantages in time, material usage, and cost, over conventional methods. Table 4 compares expenditures for an in-house B.P.I. and a single-panel V_{50} test performed in the customary manner, by outside contract.

Table 4. Comparison of In-House and Customary Methods of Obtaining V_{50} Data.

	Outside Contract (Single-Panel V_{50})	In-House (Complete B.P.I.)
Elapsed Time (Days)	14	1
Material Required (m^2)	2	1
Test Cost ($)	250	150

Estimates for performance by outside contract are very conservative in both time and money. The time is often increased due to higher priorities of the contracted agency. Also, it is not uncommon for material usage to be increased by submission of more than one test panel to validate results. This adds not only to material costs, which are substantial for Kevlar, but also to testing cost as well. Finally, charges for performance of a single V_{50} test vary considerably, depending upon the particular agency doing the work. The test cost estimate in Table 4 is the lowest currently charged.

The B.P.I. is also useful for comparing ballistic performance to fabric constructional parameters. An example of this is demonstrated in the relationship between B.P.I. and fabric weight for the five Kevlar materials.

B.P.I. vs. Fabric Weight

It is shown in Figure 6, that the ballistic resistance, as measured by B.P.I., falls off as the nominal fabric weight increases, showing that lightweight fabrics are the most efficient on an energy absorption to weight basis. This information provides a practical guideline for use in armor design.

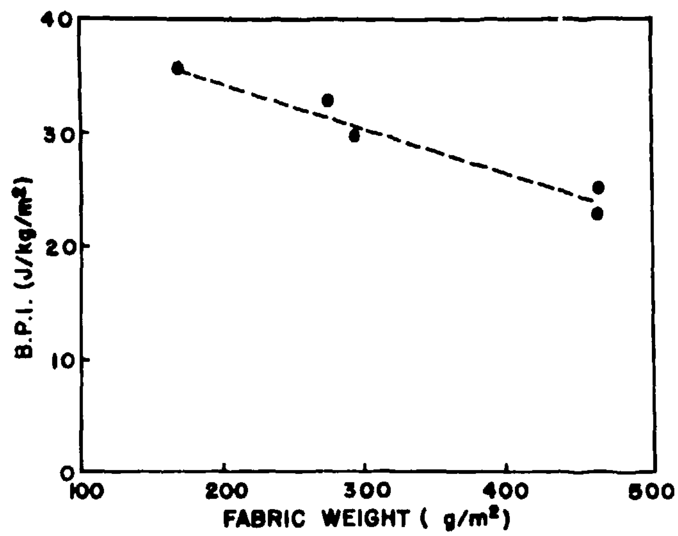

Figure 6. B.P.I. vs. Nominal Fabric Weight For Five Kevlar Materials.

Since layered armor systems are ordinarily restricted by weight limitations, this data would assist in the selection of the most efficient materials with which to achieve the design weight of an item; namely, use of more layers of light material as opposed to fewer layers of heavier material. Naturally, other considerations such as cost and ease of fabrication also influence the selection.

64

The information in Figure 6 has practical value due to its expression in terms of fabric weight, the most commonly used and easily understood constructional parameter. However, the observed trend is reflective of a more purely derived relationship between B.P.I. and the less popular parameter, fabric cover.

B.P.I. vs. Fabric Cover

Equation (1) is a convenient expression for cloth cover factor, when identical yarns are used in both warp and filling directions.

$$K_c = [(n_w + n_f)\, d - n_w n_f d^2]100 \qquad (1)$$

Where: K_c = Cloth cover factor (%)

n_w = Number of warp yarns per unit length

n_f = Number of filling yarns per unit length

d = Common yarn diameter

It gives the percentage of surface covered if viewing from a point normal to the fabric. The areas of double coverage which occur at each yarn crossover are eliminated by subtraction of the second term.

Proper analysis of fabric penetration by a ballistic missile should consider the resistance offered not only by the surface yarns, but also by these backup yarn areas at the crossovers. Therefore, a bulk cover factor, K_B, which includes the cover at the crossovers, will be used to represent the actual cover effective against missile penetration. It is defined by:

$$K_B = (n_w + n_f)\, d \qquad (2)$$

A K_B of 1.0 represents a fabric made up of sufficient yarn to cover the entire surface, if placed side by side with no interlacings. It can be shown that a K_B = 1.0, or 100% K_B cover, is equivalent to K_c = 75%.

Additional cover above this level might be expected to contribute more weight than ballistic resistance and reduce B.P.I. This is examined in Figure 7 for the five materials having K_B 's approximately between 1.0 and 2.0. A sharp decline in B.P.I. is observed with increasing K_B over this range.

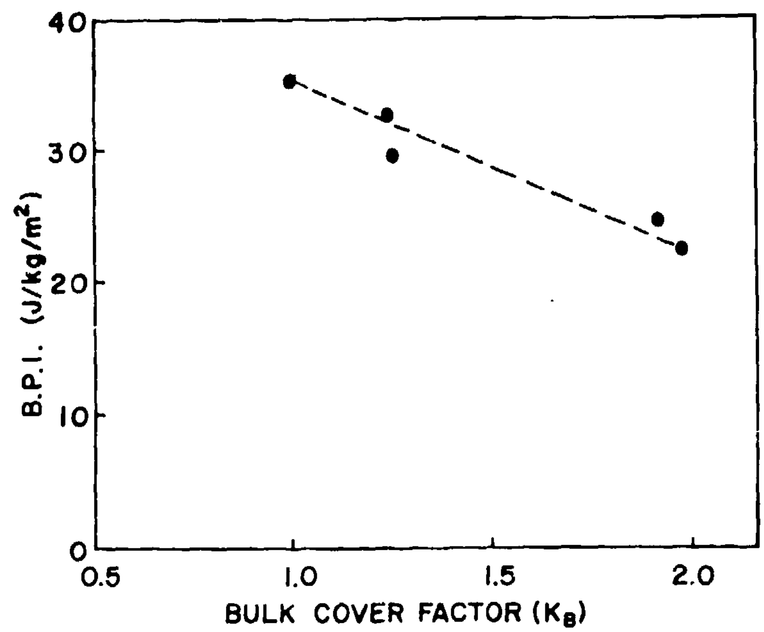

Figure 7. Effect of Bulk Cover Factor on Ballistic Performance For Five Kevlar Fabrics.

As was previously stated, the reduction in B.P.I. with increasing weight (Figure 6) reflects the influence of fabric cover illustrated in Figure 7. The similarities are due to a direct relationship between fabric weight and K_B.

It is suggested that, within practical limitations of weaveability and use, fabrics designed with a K_B approximately equal to 1.0 would provide ballistically effective alternatives to those currently in use. Fabrics made from the four commercially available Kevlar yarns would have the following weights when constructed to a K_B = 1.0.

Kevlar Yarn Tex	Fabric Weight (g/m^2)	
	K_B = 1.0	Current Use
22	133	-
44	173	-
111	219	271
167	227	475

A more comprehensive analysis of fabric performance is obtained by the inclusion of data from eight supplementary fabrics which were not tested for B.P.I., but for which V_{50}/A.D. information was available. A B.P.I. was estimated for each supplementary material - a reversal of the application for predicting V_{50}. The B.P.I.'s for all materials are shown in Figure 8 as a function of K_B. In this plot, each material is identified by weave form.

Not only is the expected downward trend in performance again observed, but a clear indication of the effect of fabric weave unfolds, with the satin weave form showing superiority at all K_B levels examined. This relationship is described by:

$$\text{B.P.I.} = 41.9 - 6.9\ K_B \tag{3}$$

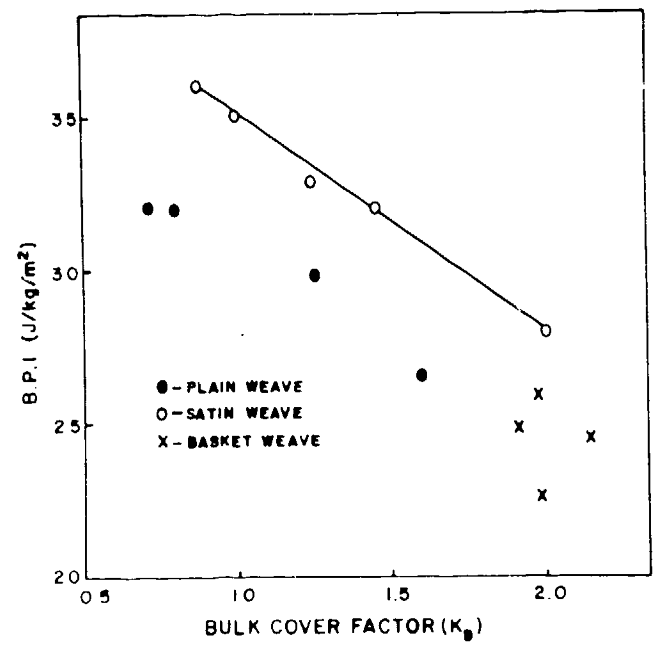

Figure 8. Effect of Weave Form and Bulk Cover Factor on Ballistic Performance Indicator.

67

Separate trend lines for the basket and plain weave forms are not distinguishable, but it appears that a relationship of the form given in equation (3) would apply as an estimate of the combined behavior of the two weave types.

It is noted that the material showing the greatest B.P.I. has a $K_B < 1.0$. The possibility may exist of advantages in cumulative cover for test panels made up of light weight materials (3). Most fabrics having K_B less than one are impractical for use in body armor because of fabrication and other problems. Consequently, the value of further investigations is questionable. Based on knowledge obtained to date, the application of equation (3) should be limited to $K_B \geq 1.0$.

Weave Effect

The superior performance of the satin weave fabrics is attributed to the lateral mobility potential inherent in the satin construction. Observation of the representative weave cross-sections in Figure 9 shows long lengths of yarn which "float" across the fabric between interlacings for the 8-harness satin form. It is speculated that these provide greater yarn mobility and transverse deformation than the more tightly constructed plain and basket weaves, which results in higher energy absorption.

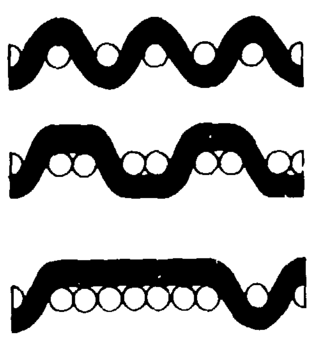

Figure 9. Generalized Cross-Sections of Three Weave Forms.

The suggestions made earlier for improved ballistic protection were based on idealized cover factor levels without regard for weave. Based on the higher B.P.I. values of the satin weaves, it is believed that the proposed fabric weights, woven into an 8-harness satin form, would offer additional advantages leading toward optimized ballistic protection.

CONCLUSIONS

The kinetic energy absorbed at V_{50} velocity for a large number of Kevlar test panels increases in direct proportion to the areal density of the panels. Based on this observed linearity, a test methodology was developed which characterizes the energy absorption at very low areal densities, through the use of research scale laboratory equipment. This relationship, which corresponds to energy absorption per unit areal density, is defined as the Ballistic Performance Indicator (B.P.I.). It can be extrapolated to predict V_{50} at practical areal densities, with high accuracy.

Use of the B.P.I. methodology to predict V_{50} provides distinct savings in time, materials, and money over conventional methods.

The use of B.P.I. to assess the effect of major fabric variables on their performance has been demonstrated. Based on relationships with parameters such as cover factor and weave, fabric forms offering improved ballistic performance have been projected. Some compromises may be necessary when practical factors such as cost, weaveability and structural integrity are considered.

REFERENCES

(1) Mascianica, F. S., "Ballistic Technology of Lightweight Armor", AMMRC-TR 79-10, U.S. Army Materials and Mechanics Research Center (February 1979).

(2) Figucia, F., "Rotatable Clamp for Ballistic Testing of Fabric", TR-80-008, U.S. Army Natick Research and Development Command (September 1979).

(3) Figucia, F., "The Effect of Kevlar Fabric Construction on Ballistic Resistance", TR 75-103CE, U.S. Army Natick Research and Development Command (April 1975).

69